

## Chapter 7 Newton's Laws of Motion

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*I have not as yet been able to discover the reason for these properties of gravity from phenomena, and I do not feign hypotheses. For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy. In this philosophy particular propositions are inferred from the phenomena, and afterwards rendered general by induction.*<sup>1</sup>

Isaac Newton

### 7.1 Force and Quantity of Matter

In our daily experience, we can cause a body to move by either pushing or pulling that body. Ordinary language use describes this action as the effect of a person's strength or *force*. However, bodies placed on inclined planes, or when released at rest and undergo free fall, will move without any push or pull. Galileo referred to a force acting on these bodies, a description of which he published in 1623 in his *Mechanics*. In 1687, Isaac Newton published his three laws of motion in the *Philosophiae Naturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"), which extended Galileo's observations. The First Law expresses the idea that when no force acts on a body, it will remain at rest or maintain uniform motion; when a force is applied to a body, it will change its state of motion.

Many scientists, especially Galileo, recognized the idea that force produces motion before Newton but Newton extended the concept of force to any circumstance that produces acceleration. When a body is initially at rest, the direction of our push or pull corresponds to the direction of motion of the body. If the body is moving, the direction of the applied force may change both the direction of motion of the body and how fast it is moving. Newton defined the force acting on an object as proportional to the acceleration of the object.

*An impressed force is an action exerted upon a body, in order to change its state, either of rest, or of uniform motion in a right line.*<sup>2</sup>

In order to define the magnitude of the force, he introduced a constant of proportionality, the *inertial mass*, which Newton called "quantity of matter".

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<sup>1</sup> Isaac Newton (1726). *Philosophiae Naturalis Principia Mathematica*, General Scholium. Third edition, page 943 of I. Bernard Cohen and Anne Whitman's 1999 translation, University of California Press.

<sup>2</sup> Isaac Newton. *Mathematical Principles of Natural Philosophy*. Translated by Andrew Motte (1729). Revised by Florian Cajori. Berkeley: University of California Press, 1934. p. 2.

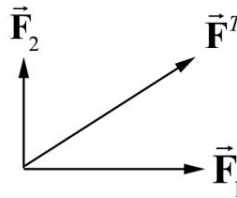
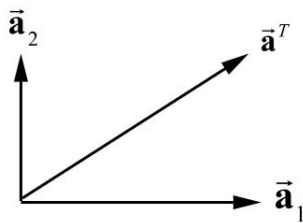
*The quantity of matter is the measure of the same, arising from its density and bulk conjointly.*

*Thus air of double density, in a double space, is quadruple in quantity; in a triple space, sextuple in quantity. The same thing is to be understood of snow, and fine dust or powders, that are condensed by compression or liquefaction, and of all bodies that are by any causes whatever differently condensed. I have no regard in this place to a medium, if any such there is, that freely pervades the interstices between the parts of bodies. It is this quantity that I mean hereafter everywhere under the name of body or mass. And the same is known by the weight of each body, for it is proportional to the weight, as I have found by experiment on pendulums, very accurately made, which shall be shown hereafter.<sup>3</sup>*

Suppose we apply an action to a body (which we refer to as the standard body) that will induce the body to accelerate with a magnitude  $|\vec{a}|$  that can be measured by an accelerometer (any device that measures acceleration). The magnitude of the force  $|\vec{F}|$  acting on the object is the product of the mass  $m_s$  with the magnitude of the acceleration  $|\vec{a}|$ . Force is a vector quantity. The direction of the force on the standard body is defined to be the direction of the acceleration of the body. Thus

$$\vec{F} \equiv m_s \vec{a} \quad (7.1.1)$$

In order to justify the statement that force is a vector quantity, we need to apply two forces  $\vec{F}_1$  and  $\vec{F}_2$  simultaneously to our body and show that the resultant force  $\vec{F}^T$  is the vector sum of the two forces when they are applied one at a time.



**Figure 7.1** Acceleration add as vectors      **Figure 7.2** Force adds as vectors.

We apply each force separately and measure the accelerations  $\vec{a}_1$  and  $\vec{a}_2$ , noting that

$$\vec{F}_1 = m_s \vec{a}_1 \quad (7.1.2)$$

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<sup>3</sup> Ibid. p. 1.

$$\vec{F}_2 = m_s \vec{a}_2 . \quad (7.1.3)$$

When we apply the two forces simultaneously, we measure the acceleration  $\vec{a}$ . The force by definition is now

$$\vec{F}^T \equiv m_s \vec{a} . \quad (7.1.4)$$

We then compare the accelerations. The results of these three measurements, and for that matter any similar experiment, confirms that the accelerations add as vectors (Figure 7.1)

$$\vec{a} = \vec{a}_1 + \vec{a}_2 . \quad (7.1.5)$$

Therefore the forces add as vectors as well (Figure 7.2),

$$\vec{F}^T = \vec{F}_1 + \vec{F}_2 . \quad (7.1.6)$$

This last statement is not a definition but a consequence of the experimental result described by Equation (7.1.5) and our definition of force.

### Example 7.1 Vector Decomposition Solution

Two horizontal ropes are attached to a post that is stuck in the ground. The ropes pull the post producing the vector forces  $\vec{F}_1 = 70 \text{ N } \hat{i} + 20 \text{ N } \hat{j}$  and  $\vec{F}_2 = -30 \text{ N } \hat{i} + 40 \text{ N } \hat{j}$  as shown in Figure 7.1. Find the direction and magnitude of the horizontal component of a third force on the post that will make the vector sum of forces on the post equal to zero.

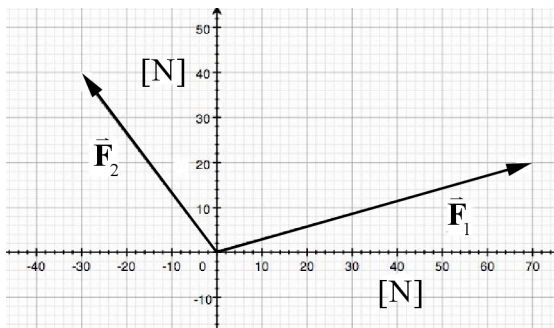


Figure 7.3 Example 7.1

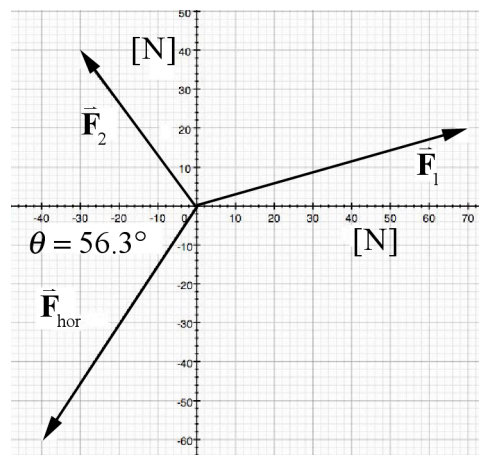


Figure 7.4 Vector sum of forces

**Solution:** Since the ropes are pulling the post horizontally, the third force must also have a horizontal component that is equal to the negative of the sum of the two horizontal forces exerted by the rope on the post Figure 7.4. Since there are additional vertical

forces acting on the post due to its contact with the ground and the gravitational force exerted on the post by the earth, we will restrict our attention to the horizontal component of the third force. Let  $\vec{F}_3$  denote the sum of the forces due to the ropes. Then we can write the vector  $\vec{F}_3$  as

$$\begin{aligned}\vec{F}_3 &= (F_{1x} + F_{2x}) \hat{i} + (F_{1y} + F_{2y}) \hat{j} = (70 \text{ N} + -30 \text{ N}) \hat{i} + (20 \text{ N} + 40 \text{ N}) \hat{j} \\ &= (40 \text{ N}) \hat{i} + (60 \text{ N}) \hat{j}\end{aligned}$$

Therefore the horizontal component of the third force of the post must be equal to

$$\vec{F}_{hor} = -\vec{F}_3 = -(\vec{F}_1 + \vec{F}_2) = (-40 \text{ N}) \hat{i} + (-60 \text{ N}) \hat{j}.$$

The magnitude is  $|\vec{F}_{hor}| = \sqrt{(-40 \text{ N})^2 + (-60 \text{ N})^2} = 72 \text{ N}$ . The horizontal component of the force makes an angle

$$\theta = \tan^{-1} \left[ \frac{60 \text{ N}}{40 \text{ N}} \right] = 56.3^\circ$$

as shown in the figure above.

### 7.1.1 Mass Calibration

So far, we have only used the standard body to measure force. Instead of performing experiments on the standard body, we can calibrate the masses of all other bodies in terms of the standard mass by the following experimental procedure. We shall refer to the mass measured in this way as the **inertial mass** and denote it by  $m_{in}$ .

We apply a force of magnitude  $F$  to the standard body and measure the magnitude of the acceleration  $a_s$ . Then we apply the same force to a second body of unknown mass  $m_{in}$  and measure the magnitude of the acceleration  $a_{in}$ . Since the same force is applied to both bodies,

$$F = m_{in} a_{in} = m_s a_s, \quad (1.7)$$

Therefore the ratio of the inertial mass to the standard mass is equal to the inverse ratio of the magnitudes of the accelerations,

$$\frac{m_{in}}{m_s} = \frac{a_s}{a_{in}}. \quad (1.8)$$

Therefore the second body has inertial mass equal to

$$m_{in} \equiv m_s \frac{a_s}{a_{in}}. \quad (1.9)$$

This method is justified by the fact that we can repeat the experiment using a different force and still find that the ratios of the acceleration are the same. For simplicity we shall denote the inertial mass by  $m$ .

## 7.2 Newton's First Law

The First Law of Motion, commonly called the "Principle of Inertia," was first realized by Galileo. (Newton did not acknowledge Galileo's contribution.) Newton was particularly concerned with how to phrase the First Law in Latin, but after many rewrites Newton perfected the following expression for the First Law (in English translation):

*Law 1: Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.*

*Projectiles continue in their motions, so far as they are not retarded by the resistance of air, or impelled downwards by the force of gravity. A top, whose parts by their cohesion are continually drawn aside from rectilinear motions, does not cease its rotation, otherwise than as it is retarded by air. The greater bodies of planets and comets, meeting with less resistance in freer spaces, preserve their motions both progressive and circular for a much longer time.<sup>4</sup>*

The first law is an experimental statement about the motions of bodies. When a body moves with constant velocity, there are either no forces present or there are forces acting in opposite directions that cancel out. If the body changes its velocity, then there must be an acceleration, and hence a total non-zero force must be present. We note that velocity can change in two ways. The first way is to change the magnitude of the velocity; the second way is to change its direction.

After a bus or train starts, the acceleration is often so small we can barely perceive it. We are often startled because it seems as if the station is moving in the opposite direction while we seem to be still. Newton's First Law states that there is no physical way to distinguish between whether we are moving or the station is, because there is essentially no total force present to change the state of motion. Once we reach a constant velocity, our minds dismiss the idea that the ground is moving backwards because we think it is impossible, but there is no actual way for us to distinguish whether the train is moving or the ground is moving.

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<sup>4</sup> Ibid. p. 13.

### 7.3 Momentum, Newton's Second Law and Third Law

Newton began his analysis of the cause of motion by introducing the quantity of motion:

***Definition: Quantity of Motion:***

*The quantity of motion is the measure of the same, arising from the velocity and quantity of matter conjointly.*

*The motion of the whole is the sum of the motion of all its parts; and therefore in a body double in quantity, with equal velocity, the motion is double, with twice the velocity, it is quadruple.<sup>5</sup>*

Our modern term for quantity of motion is *momentum* and it is a vector quantity

$$\vec{p} = m\vec{v} . \quad (7.3.1)$$

where  $m$  is the inertial mass and  $\vec{v}$  is the velocity of the body (velocity is a vector quantity). Newton's Second Law is the most important experimental statement about motion in physics.

*Law II: The change of motion is proportional to the motive force impressed, and is made in the direction of the right line in which that force is impressed.*

*If any force generates a motion, a double force will generate double the motion, a triple force triple the motion, whether that force is impressed altogether and at once or gradually and successively. And this motion (being always directed the same way with the generating force), if the body moved before, is added or subtracted from the former motion, according as they directly conspire with or are directly contrary to each other; or obliquely joined, when they are oblique, so as to produce a new motion compounded from the determination of both.<sup>6</sup>*

Suppose that a force is applied to a body for a time interval  $\Delta t$ . The impressed force or *impulse* (a vector quantity  $\vec{I}$ ) that we denote by produces a change in the momentum of the body,

$$\vec{I} = \vec{F}\Delta t = \Delta\vec{p} . \quad (7.3.2)$$

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<sup>5</sup> Ibid. p. 1.

<sup>6</sup> Ibid. p. 13.

From the commentary to the second law, Newton also considered forces that were applied continually to a body instead of impulsively. The instantaneous action of the total force acting on a body at a time  $t$  is defined by taking the mathematical limit as the time interval  $\Delta t$  becomes smaller and smaller,

$$\vec{F} = \lim_{\Delta t \rightarrow 0} \frac{\Delta \vec{p}}{\Delta t} \equiv \frac{d\vec{p}}{dt} . \quad (7.3.3)$$

When the mass remains constant in time, the Second Law can be recast in its more familiar form,

$$\vec{F} = m \frac{d\vec{v}}{dt} . \quad (7.3.4)$$

Because the derivative of velocity is the acceleration, the force is the product of mass and acceleration,

$$\vec{F} = m \vec{a} . \quad (7.3.5)$$

Because we defined force in terms of change in motion, the Second Law appears to be a restatement of this definition, and devoid of predictive power since force is only determined by measuring acceleration. What transforms the Second Law from just merely a definition is the additional input that comes from *force laws* that are based on experimental observations on the interactions between bodies. Throughout this book, we shall investigate these force laws and learn to use them in order to determine the left-hand side of Newton's Second Law.

The right-hand-side of Newton's Second Law is the product of mass with acceleration. Acceleration is a mathematical description of how the velocity of a body changes. If we know the acceleration of a body we can in principle, predict the velocity and position of that body at all future times by integration techniques.

## 7.4 Newton's Third Law: Action-Reaction Pairs

Newton realized that when two bodies interact via a force, then the force on one body is equal in magnitude and opposite in direction to the force acting on the other body.

*Law III: To every action there is always opposed an equal reaction: or, the mutual action of two bodies upon each other are always equal, and directed to contrary parts.*

*Whatever draws or presses another is as much drawn or pressed by that other. If you press on a stone with your finger, the finger is also pressed by the stone.<sup>7</sup>*

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<sup>7</sup> Ibid p. 13.



The Third Law, commonly known as the “action-reaction” law, is the most surprising of the three laws. Newton’s great discovery was that when two objects interact, they each exert the same magnitude of force on each other. We shall refer to objects that interact as an *interaction pair*.

Consider two bodies engaged in a mutual interaction. Label the bodies 1 and 2 respectively. Let  $\vec{F}_{1,2}$  be the force on body 2 due to the interaction with body 1, and  $\vec{F}_{2,1}$  be the force on body 1 due to the interaction with body 2. These forces are depicted in Figure 7.5.



**Figure 7.5** Action-reaction pair of forces

These two vector forces are equal in magnitude and opposite in direction,

$$\vec{F}_{1,2} = -\vec{F}_{2,1}. \quad (7.4.1)$$

With these definitions, the three laws and force laws constitute *Newtonian Mechanics*, which will be able to explain a vast range of phenomena. Newtonian mechanics has important limits. It does not satisfactorily explain systems of objects moving at speeds comparable to the speed of light ( $v > 0.1c$ ) where we need the theory of special relativity, nor does it adequately explain the motion of electrons in atoms, where we need *quantum mechanics*. We also need *general relativity* and *cosmology* to explain the large-scale structure of the universe.